

7. Waste

Certain waste management and treatment activities are sources of greenhouse gas emissions. Particularly the anaerobic decomposition of organic wastes by bacteria can result in the generation of methane (C). Currently, anaerobic decomposition processes in landfills are estimated to be the largest anthropogenic source of methane emissions in the United States, accounting for just over 36 percent of the total (see Figure 7-1). Smaller amounts of methane are emitted from wastewater systems by bacteria used in various treatment processes. Wastewater treatment systems are also a potentially significant source of nitrous oxide (N₂O) emissions; however, methodologies are not currently available to develop a complete estimate. Emissions from the treatment of the human sewage component of wastewater were estimated, however, using a simplified methodology. Waste combustion, both in incinerators and through open burning, is a small source of N₂O. Nitrogen oxide (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) are emitted by each of these sources, but are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste sector is presented in Table 7-1 and Table 7-2.

Landfills

Landfills are the largest anthropogenic source of methane (CH₄) emissions in the United States. In 1996, emissions were approximately 65.1 MMTCE (11.4 Tg), or just over 36 percent of U.S. methane emissions (see Table 7-3 and Table 7-4). Emissions from municipal solid waste (MSW) landfills, which received about 62 percent of the total solid waste generated in the United States, accounted for about 93 percent of total landfill emissions, while industrial landfills accounted for the remaining. There are over 6,000 landfills in the United States, with 1,300 of the largest landfills receiving almost all the waste and generating the vast majority of the emissions.

Methane emissions result from the decomposition of organic landfill materials such as yard waste, household garbage, food waste, and paper. This decomposition process is a natural mechanism through which microorganisms derive energy. After being placed in a landfill, organic waste first decomposes aerobically (in the presence of oxygen) and is then attacked by anaerobic bacteria, which convert organic matter to substances such as cellulose, amino acids, and sugars. These simple substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. Methane producing anaerobic

Figure 7-1

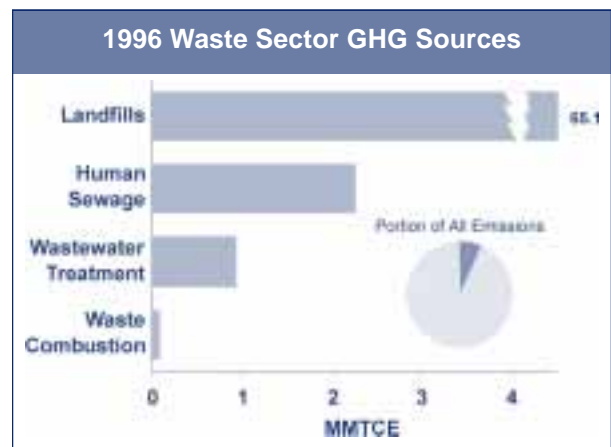


Table 7-1: Emissions from the Waste Sector (MMTCE)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CH₄	57.1	58.4	58.7	60.6	62.5	64.5	66.0
Landfills	56.2	57.6	57.8	59.7	61.6	63.6	65.1
Wastewater Treatment	0.9	0.9	0.9	0.9	0.9	0.9	0.9
N₂O	1.4	1.4	1.5	1.5	1.5	1.5	1.5
Human Sewage	2.1	2.1	2.2	2.2	2.3	2.2	2.3
Waste Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	59.3	60.6	61.0	62.8	64.8	66.9	68.4

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from the Waste Sector (Tg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
CH₄	10.0	10.2	10.3	10.6	10.9	11.3	11.5
Landfills	9.8	10.0	10.1	10.4	10.8	11.1	11.4
Wastewater Treatment	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N₂O	+	+	+	+	+	+	+
Human Sewage	+	+	+	+	+	+	+
Waste Combustion	+	+	+	+	+	+	+

+ Does not exceed 0.05 Tg
Note: Totals may not sum due to independent rounding.

bacteria then convert these fermentation products into stabilized organic materials and a biogas consisting of approximately 50 percent carbon dioxide and 50 percent methane by volume. In general, the CO₂ emitted is of biogenic origin and primarily results from the decomposition—either aerobic or anaerobic—of organic matter such as food or yard wastes.¹ The percentage of carbon dioxide in the biogas released from a landfill may be smaller because some CO₂ dissolves in landfill water (Bingemer and Crutzen 1987). Methane production typically begins one or two years after waste placement in a landfill and may last from 10 to 60 years.

Between 1990 and 1996, estimates of methane emissions from landfills have increased slightly. The relatively constant emissions estimates are a result of two counter-acting factors: (1) the amount of MSW in landfills contributing to methane emissions has increased (thereby increasing the potential for emissions), and (2) the amount of landfill gas collected and combusted by landfill operators has also increased (thereby reducing emissions).

Methane emissions from landfills are a function of several factors, including: the total amount of MSW landfilled over the last 30 years, which is related to total MSW landfilled per year; composition of the waste in place; the amount of methane that is recovered and either flared or used for energy purposes; and the amount of methane oxidized in landfills before being released into the atmosphere. The estimated total quantity of waste in place contributing to emissions increased from about 4,926 teragrams in 1990 to 5,676 teragrams in 1996, an increase of 15 percent (see Annex I). During this same period, the estimated methane recovered and flared from landfills increased as well. In 1990, for example, approximately 1.5 teragrams (Tg) of methane were recovered and combusted (i.e., used for energy or flared) from landfills. In 1992, the estimated quantity of methane recovered and combusted increased to 1.8 Tg.²

Over the next several years, the total amount of MSW generated is expected to continue increasing. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In ad-

¹ Emissions and sinks of biogenic carbon are accounted for under the Land-Use Change and Forestry sector.

² EPA is presently reviewing new data on landfill gas recovery and flaring. It is anticipated that the national total for methane recovery and flaring will be significantly larger based on this new information.

Table 7-3: CH₄ Emissions from Landfills (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996
MSW Landfills	60.6	61.9	63.8	65.5	67.3	69.2	70.6
Industrial Landfills	4.2	4.3	4.4	4.5	4.6	4.8	4.9
Recovered	(8.6)	(8.6)	(10.3)	(10.3)	(10.3)	(10.3)	(10.3)
Net Emissions	56.2	57.6	57.8	59.7	61.6	63.6	65.1

Note: Totals may not sum due to independent rounding.

Table 7-4: CH₄ Emissions from Landfills (Tg)

Activity	1990	1991	1992	1993	1994	1995	1996
MSW Landfills	10.6	10.8	11.1	11.4	11.7	12.1	12.3
Industrial Landfills	0.7	0.7	0.8	0.8	0.8	0.8	0.8
Recovered	(1.5)	(1.5)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)
Net Emissions	9.8	10.0	10.1	10.4	10.8	11.1	11.4

Note: Totals may not sum due to independent rounding.

dition, the quantity of methane that is recovered and either flared or used for energy purposes is expected to increase, partially as a result of a new regulation that will require large landfills to collect and combust landfill gas. The impact of such shifts in activity on emissions cannot be fully assessed at this time.

Methodology

Based on the available information, methane emissions from landfills were estimated to equal methane production from municipal landfills, plus methane produced by industrial landfills, minus methane recovered and combusted, and minus the methane oxidized before being released into the atmosphere.

The methodology for estimating CH₄ emissions from municipal landfills is based on an updated model that tracks changes in the population of landfills in the United States over time. This model is based on the pattern of actual waste disposal by each individual landfill surveyed by the EPA's Office of Solid Waste in 1987. A second model was employed to estimate emissions from the landfill population data (EPA 1993). For each landfill in the data set, the amount of waste in place contributing to methane generation was estimated using its year of opening, its waste acceptance rate, and total waste disposed in landfills. Data on national waste disposed in landfills each year was apportioned by landfill. Emissions from municipal landfills were then estimated by multiplying the quantity of waste contributing to emis-

sions by emission factors (EPA 1993). For further information see Annex I.

To estimate landfill gas recovered per year, data on current and planned landfill gas recovery projects in the United States were obtained from Governmental Advisory Associates (GAA 1994). The GAA report, considered to be the most comprehensive source of information on gas recovery in the United States, has estimates for gas recovery in 1990 and 1992. In addition, a number of landfills were believed to recover and flare methane without energy recovery and were not included in the GAA database. To account for the amount of methane flared without energy recovery, the estimate of gas recovered was increased by 25 percent (EPA 1993).

The amount of methane oxidized was assumed to be 10 percent of the methane generated. Methane recovered and oxidized was subtracted from the methane generated from municipal and industrial landfills to arrive at net methane emissions. Emissions from industrial sites were assumed to be a fixed percentage of total emissions from municipal landfills.

Data Sources

The model, including actual waste disposal data from individual landfills, was developed from a survey performed by the EPA Office of Solid Waste (EPA 1988). National landfill waste disposal data for 1988 through 1996 were obtained from *Biocycle* (1997). Documentation on the landfill methane emissions methodology em-

ployed is available in EPA's "Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress" (EPA 1993). Emission factors were taken from Bingemer and Crutzen (1987) and the Governmental Advisory Associates (GAA 1994).

Uncertainty

There are several uncertainties associated with the estimates of methane emissions from landfills. The primary one concerns the characterization of landfills. There is a lack of information on the area landfilled and total waste in place (the fundamental factors that affect methane production). In addition, little information is available on the quantity of methane flared at non-energy related projects and the number of landfill closures. Finally, the statistical model used to estimate emissions is based upon methane generation at landfills that currently have developed energy recovery projects, and may not precisely capture the relationship between emissions and various physical characteristics of individual landfills. Overall, uncertainty is estimated to be roughly ± 30 percent.

Wastewater Treatment

The breakdown of organic material in wastewater treatment systems produces methane when it occurs under anaerobic conditions. During collection and treatment, wastewater may be incidentally as well as deliberately maintained under anaerobic conditions. The methane produced during deliberate anaerobic treatment is typically collected and flared or combusted for energy. However, whenever anaerobic conditions develop, some of the methane generated is incidentally released to the atmosphere. Untreated wastewater may also produce methane if held under anaerobic conditions.

Organic content, expressed in terms of biochemical oxygen demand (BOD), determines the methane producing potential of wastewater. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes. Under

Table 7-5: CH₄ Emissions from Domestic Wastewater Treatment

Year	MMTCE	Tg
1990	0.9	0.2
1991	0.9	0.2
1992	0.9	0.2
1993	0.9	0.2
1994	0.9	0.2
1995	0.9	0.2
1996	0.9	0.2

anaerobic conditions, however, wastewater with higher BOD concentrations will produce more methane than wastewater with lower BOD. The amount of methane produced is driven by the extent to which the organic material is broken down under anaerobic versus aerobic conditions.

In 1996, methane emissions from municipal wastewater were 0.9 MMTCE (0.2 Tg), or less than one percent of total U.S. methane emissions. Emissions have increased slightly since 1990 reflecting the increase in the U.S. human population. No estimates have been developed to indicate any changes in the manner in which wastewater is managed in the United States during this period. Table 7-5 provides emission estimates from domestic wastewater treatment.

At this time, data are not sufficient to estimate methane emissions from industrial wastewater sources. Further research is ongoing at the EPA to better quantify emissions from this source.

Methodology

Wastewater methane emissions are estimated using the default IPCC methodology (IPCC/UNEP/OECD/IEA 1997). The total population for each year was multiplied by a wastewater BOD production rate to determine total wastewater BOD produced. It was assumed that, per capita, 0.05 kilograms of wastewater BOD³ is produced per day and that 15 percent of wastewater BOD₅ is anaerobically digested. This proportion of BOD was then multiplied by an emission factor of 0.22 Gg of CH₄ per Gg of BOD₅.

³ The 5 day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1972).

Table 7-6: U.S. Population (millions) and Wastewater BOD Produced (Gg)

Year	Population	BOD5*
1990	250.7	4,578
1991	253.6	4,631
1992	256.5	4,685
1993	259.2	4,733
1994	261.7	4,779
1995	264.2	4,824
1996	266.5	4,867

* The 5 day biochemical oxygen demand (BOD) measurement (Metcalf and Eddy 1972)

Data Sources

Human population data for 1990 to 1996 were supplied by the U.S. Census Bureau (1997). The emission factor employed was taken from Metcalf & Eddy (1972). Table 7-6 provides U.S. population and wastewater BOD data.

Uncertainty

Domestic wastewater emissions estimates are highly uncertain due to the lack of data on the occurrence of anaerobic conditions in treatment systems, especially incidental occurrences. It is also believed that industrial wastewater is responsible for significantly more methane emissions than domestic wastewater treatment.

Human Sewage

Human sewage is transported for treatment in the form of domestic wastewater. Nitrous oxide (N_2O) is emitted from both domestic and industrial wastewater containing nitrogen-based organic matter and is produced through natural processes known as nitrification and denitrification. Nitrification occurs aerobically and converts ammonia into nitrate, while denitrification occurs anaerobically, and converts nitrate to N_2O . It is estimated that the amount of N_2O emitted from wastewater treatment plants accounts for approximately 5 to 10 percent of annual global discharge (Spector 1997, McElroy et al. 1978). Human sewage is believed to constitute a significant portion of the material responsible for N_2O emissions from wastewater (Spector 1997). There is insuffi-

cient information available at this time to estimate emissions from industrial wastewater and the other components of domestic wastewater. In general, N_2O generation in wastewater systems is affected by temperature, pH, biochemical oxygen demand (BOD), and nitrogen concentration. BOD is the amount of dissolved oxygen used by aerobic microorganisms to completely consume the available organic matter (Metcalf and Eddy 1972).

Emissions of N_2O from human sewage treated in wastewater systems was estimated to be 2.3 MMTCE (27 Gg) in 1996. An increase in the U.S. population and the per capita protein intake resulted in an overall increase of 8 percent in N_2O emissions from human sewage between 1990 and 1996 (see Table 7-7).

Table 7-7: N_2O Emissions from Human Sewage

Year	MMTCE	Gg
1990	2.1	25
1991	2.1	25
1992	2.2	26
1993	2.2	26
1994	2.3	27
1995	2.2	26
1996	2.3	27

Methodology

Nitrous oxide emissions from human sewage were estimated using the IPCC default methodology (IPCC/ UNEP/OECD/IEA 1997). The equation in IPCC was modified slightly to convert N_2O -N to N_2O by using a conversion factor of the atomic weight of N_2O to that of N_2 (44/28). This is illustrated below:

$$N_2O(s) = (\text{Protein}) \times (\text{Frac}_{NPR}) \times (\text{NR People}) \times (\text{EF}) \times (44/28)$$

where,

$N_2O(s)$ = N_2O emissions from human sewage

Protein = Annual, per capita protein consumption

Frac_{NPR} = fraction of nitrogen in protein

NR People = U.S. population

EF = Emission factor

(44/28) = The atomic weight ratio of N_2O to N_2

Data Sources

U.S. population data were taken from the U.S. Census Bureau (1997). Data on the annual per capita protein consumption were provided by the United Nations Food and Agriculture Organization (FAO 1997). Because data on protein intake were unavailable for 1996, the average value of per capita protein consumption over the years 1990 through 1995 was used (see Table 7-8). An emission factor has not been specifically estimated for the United States. As a result, the default IPCC value (0.01 kg N₂O-N/kg sewage-N produced) was applied. Similarly, the fraction of nitrogen in protein (0.16 kg N/kg protein) was also obtained from IPCC/UNEP/OECD/IEA (1997).

Table 7-8: U.S. Population (millions) and Average Protein Intake (kg/person/year)

Year	Population	Protein
1990	250.7	39.06
1991	253.6	39.42
1992	256.5	39.79
1993	259.2	40.15
1994	261.7	40.88
1995	264.2	39.79
1996	266.5	39.79

Uncertainty

The U.S. population (NR people) and per capita protein intake data (Protein) are believed to be highly certain. There is significant uncertainty, however, in the emission factor (EF) due to regional differences that would likely affect N₂O emissions but are not accounted for in the default IPCC factor. In contrast, the fraction of nitrogen in protein (Frac_{NPR}) is believed to be quite accurate. Despite the increase in N₂O emissions from 1990 through 1996, these estimates from human sewage are significantly lower than other more recent estimates (Spector 1997) of total N₂O emissions from both domestic and industrial wastewater treatment. EPA is currently supporting further research to develop a comprehensive estimate of emissions from this source.

⁴ Emissions of carbon dioxide from the combustion of petroleum-based plastics are accounted for under CO₂ from fossil fuel combustion as a non-fuel use of petroleum.

Waste Combustion

Waste combustion involves the burning of garbage and non-hazardous solids, called municipal solid waste (MSW), and has been identified as a source of nitrous oxide (N₂O) emissions.⁴ In 1992, there were over 160 municipal waste combustion plants in the United States (EPA 1997b). Emissions from this source are dependent on the types of waste burned and combustion temperatures (De Soete 1993). Nitrous oxide emissions from MSW combustion were estimated to be 0.1 MMTCE (1 Gg) in 1996, and have fluctuated only slightly since 1990 (see Table 7-9).

Table 7-9: N₂O Emissions from Waste Combustion

Year	MMTCE	Gg
1990	0.1	1
1991	0.1	1
1992	0.1	1
1993	0.1	1
1994	0.1	1
1995	0.1	1
1996	0.1	1

Methodology

Estimates of nitrous oxide emissions from MSW combustion in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emission Factors (EPA 1997a). It is based upon the quantity of MSW combusted at waste combustion facilities and an emission factor of N₂O emission per unit mass of waste combusted (30 g N₂O/metric ton MSW).

Data Sources

Data on the quantity of MSW generated and combusted was taken from the April 1997 issue of *BioCycle* (Goldstein 1997). Table 7-10 provides MSW generation and percentage combustion data. The emission factor of N₂O emissions per quantity of MSW combusted was taken from De Soete (1993).

Table 7-10: Municipal Solid Waste Generation (Metric Tons) and Percent Incinerated

Year	Waste Generation	Combusted (%)
1990	266,541,881	11.5
1991	254,796,765	10.0
1992	264,843,388	11.0
1993	278,572,955	10.0
1994	293,109,556	10.0
1995	296,586,430	10.0
1996	297,268,188	10.0

Table 7-11: U.S. Municipal Solid Waste Combusted by Data Source (Metric Tons)

Year	BioCycle	EPA
1990	30,652,316	28,958,820
1991	25,479,677	30,256,974
1992	29,132,773	29,675,982
1993	27,857,295	29,884,776
1994	29,310,956	29,494,422
1995	29,658,643	30,384,066
1996	29,726,819	NA

NA (Not Available)

Uncertainty

As with other combustion related sources of nitrous oxide, emissions are affected by combustion conditions. In part, because insufficient data exists to provide detailed estimates of N₂O emissions for individual combustion facilities, the estimates presented are highly uncertain. MSW combustion data published in *BioCycle* were compared with data published by the EPA's Office of Solid Waste (EPA 1997b) and were found to be relatively consistent (see Table 7-11). The emission factor for N₂O from MSW combustion facilities has also been found to vary by an order of magnitude (between 25 and 293 g N₂O/metric ton MSW combusted) (Watanabe, et al. 1992).

Waste Sources of Criteria Pollutants

In addition to the main greenhouse gases addressed above, waste generating and handling processes are sources of criteria air pollutant emissions. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and nonmethane volatile organic compounds (NMVOCs) from the Waste sector for the years 1990 through 1996 are provided in Table 7-12.

Table 7-12: Emissions of NO_x, CO, and NMVOC from Waste (Gg)

Gas/Source	1990	1991	1992	1993	1994	1995	1996
NO_x	83	86	87	112	103	89	91
Landfills	+	+	+	1	1	1	1
Wastewater Treatment	+	+	+	+	+	+	+
Waste Combustion ^a	82	85	86	107	99	88	89
Miscellaneous ^b	+	1	1	4	3	1	1
CO	979	1,012	1,032	1,133	1,111	1,075	1,091
Landfills	1	1	2	2	2	2	2
Wastewater Treatment	+	+	+	+	+	+	+
Waste Combustion ^a	978	1,011	1,030	1,130	1,108	1,073	1,089
Miscellaneous ^b	+	+	+	1	1	1	1
NMVOCs	895	907	916	949	949	968	393
Landfills	58	60	63	67	73	68	20
Wastewater Treatment	57	58	61	63	64	61	58
Waste Combustion ^a	222	227	230	256	248	237	240
Miscellaneous ^b	558	562	563	563	564	602	75

^a Includes waste incineration and open burning (EPA 1997)

^b Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 Gg

Methodology and Data Sources

These emission estimates were taken directly from the EPA's *National Air Pollutant Emissions Trends, 1900-1996* (EPA 1997b). This EPA report provides emission estimates of these gases by sector, using a “top down” estimating procedure³⁴emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which relate the quantity of emissions to

the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997a). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA data bases.

Uncertainty

Uncertainties in these estimates are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.